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Experimental study on the stable steam jet in subcooled water flow in a rectangular mix chamber

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ABSTRACT

Two-phase Flow Steam Injector (TFSI) was a simple device without moving parts, which had been used in several industrial applications. As an important process of the TFSI, steam-water Direct Contact Condensation (DCC) in stagnant water pool had been widely investigated. DCC had different features when occurring in a confined channel in water flow, which is more similar to the DCC process of that in TFSI. In present work, direct contact condensation of stable steam jet in subcooled water flow in a rectangular mix chamber was investigated experimentally. Rectangular steam and water nozzles were adopted to form a quasi-planar structural flow flied and two different stable steam jets including conical jet and ellipsoidal jet were observed. The transition from stable steam jet to divergent jet was observed and the transition criterion was also established. A three-dimensional regime diagram was presented and discussed based on steam mass flux, water mass flux and inlet water temperature. In addition, temperature and pressure distributions on the bottom wall center for stable steam jet were measured. The peaks in temperature distributions evidenced the compression wave, whilst the nadirs in pressure distributions were evidence to the expansion wave. Furthermore, average heat transfer coefficients predicted by interfacial transport model due to turbulent intensity were in the range of 3.83–6.24 MW/m^2 K, which were in the same order of magnitude with previous investigations, and the discrepancies between predicted and experimental values were within ±30%.

1. Introduction

Two-phase Flow Steam Injector (TFSI) is a simple device without moving parts. Due to the compact configuration and efficient heat transfer characteristics, it has been widely used in several industrial applications, such as nuclear energy, electric power and petrochemical [1,2].

The phenomenon of steam-water Direct Contact Condensation (DCC) heat transfer is the core process of TFSI. Many investigations including flow pattern, regime diagram and heat transfer characteristics had been conducted to have a fundamental understanding of DCC in stagnant water pool [3]. When the steam was injected downward into subcooled water through a pipe, three flow patterns including oscillatory jet, steam chugging and oscillatory bubble were reported by Chan and Lee [4]. Simpson and Chan [5] observed periodic interface motion in subsonic steam jet and the processes of bubble formation, growth and detachment were clearly distinguished. Chun et al. [6] reported two different flow patterns of stable jet including conical jet and ellipsoidal jet, the results indicated that the conical jet occurred at small steam mass flux whilst the ellipsoidal jet occurred at large. Liang and Griffith [7] observed steam chugging, bubbling, oscillatory jet and stable jet, and the transition criteria between steam chugging, bubbling and jetting were proposed. Petrovic de With et al. [8] presented a regime diagram based on steam mass flux, subcooled water temperature and nozzle diameter. Wu et al. [9–11] experimentally investigated sonic and supersonic steam jet submerged in quiescent subcooled water and six typical shapes were observed. By considering the effects of steam mass flux, water temperature and pressure ratio, a regime diagram was also investigated. In addition, temperature distributions were discussed and the heat transfer coefficients were found to be within 0.63–3.44 MW/m^2 K. Kim et al. [12] developed three interfacial transport models including turbulent intensity interfacial transport model, surface renewal model and shear stress model to evaluate the heat transfer characteristics. Additionally,

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Nomenclature

A_i	interface area, m^2	P_w	inlet water pressure, MPa
A_e	steam nozzle exit area, m^2	Pr	water Prandtl number
c_p	water specific heat, J/kg K	Re_w	water Reynolds number at water nozzle exit
d_{he}	steam nozzle exit equivalent diameter, m	Re_f^s	steam-water Reynolds number, $v_e d_{he}/\nu_w$
G_s	steam mass flux at steam nozzle throat, kg/m^2 s	St	Stanton number
G_e	steam mass flux at steam nozzle exit, kg/m^2 s	T_s	steam temperature
G_w	water mass flux at water nozzle exit, kg/m^2 s	T_w	water temperature, K
h_{fg}	latent heat of condensation, kJ/kg	T_{wo}	outlet water temperature, K
h_{ave}	average heat transfer coefficient, MW/m^2 K	ΔT_{sub}	logarithmic mean temperature difference, K
Ja	Jacob number	v_e	steam velocity at steam nozzle exit, m/s
m_e	steam mass flow rate, kg/s	ρ_w	water density, kg/m^3
n	ratio of the thermal boundary layer thickness to the eddy size	ρ_e	steam density at steam nozzle exit, kg/m^3
P_s	inlet steam pressure, MPa	ν_w	water kinetic viscosity, m^2/s

numerical method was also adopted to investigate the steam-water DCC phenomenon [13,14].

Steam-water DCC had different features when occurring in a confined channel in in water flow, which is more similar to the process of that in the TFSI. Investigations on the steam-water DCC in a confined channel in water flow would provide more information on the optimization design and safe operation of the TFSI. Previous investigations mostly concentrated on flow characteristics and global performance [15,16], heat transfer characteristics were little concerned. Yan et al. [15] investigated the pressure distributions of an injector, and found that the pressure was almost constant in the mixing chamber. On the other hand, Celata et al. [17–19] conducted experimental and theoretical research on DCC of stagnant saturated and superheated steam on slowly moving water on a horizontal surface. A theoretical model for predicting direct contact condensation was proposed and found that heat transfer resistance mainly lay on water side. Deberne et al. [20] carried out visualized research on heat transfer performance of DCC, and found that the cross-sectional average vapor void fraction was increasing during condensation. Recently, Xu et al. [21,22] experimentally studied steam jet in cross and concurrent flow of water in a vertical pipe, and five different shapes: hemispherical, conical, ellipsoidal, cylinder and divergent were identified visually, in the concurrent water flow, heat transfer coefficients were reported to be in the range of 0.34–11.36 MW/m^2 K. Zong et al. [23] experimentally investigated the DCC of steam jet in water flow in a rectangular mix chamber, and found that the penetration length would decrease with increasing water flow rate. Yang et al. [24] investigated steam–air mixture in subcooled water flow, and found that steam–air mixture would lead to reduction of heat transfer.

In the previous studies, steam-water DCC was almost investigated in initially stagnant water pool or water flow by circular nozzles or pipes, steam jet was condensed by water all around, which formed a three-dimensional structural view field, inner structure of the steam jet could not be observed directly. To have a further understanding of the steam-water DCC process occurring in the TFSI, the purpose of this paper was to investigate the stable steam jet in subcooled water flow in a confined rectangular mix chamber. In present work, the water mass flux was identified as a new parameter to present the three-dimensional regime diagram and the transition criterion for stable jet to divergent jet was established, and the temperature and pressure distributions on the bottom wall center along steam jet were measured and discussed, in addition, the interfacial transport model due to turbulent intensity was used to predict the average heat transfer coefficient and a correlation for predicting average heat transfer coefficient was also given.

2. Experimental apparatus

The experimental apparatus mainly consists of a test section, an electric steam generator, a feed pump, a return pump, two water tanks, a high-speed camera, a cooling tower and some valves, as shown in Fig. 1. Steam supply is taken from the steam generator continuously with electric heaters of 330 kW and maximum flow rate of 0.11 kg/s. The steam flow rate is controlled by a valve manually and all the steam lines are wrapped by fiberglass insulation. Filtered water is derived from a single-stage horizontal shaft centrifugal pump and the water flow rate is controlled by valves on feed and by-pass lines. The Phantom V611 type high-speed camera is set as 5 kHz in experiments.

The test section is made of stainless steel and two pieces of tempered glass are installed at front and back of the test section for observation and filming. The convergent-divergent rectangular steam nozzle is inserted into the test section by soldering, as shown in Fig. 2(a). The steam nozzle throat height and width are both 8 mm, whilst 10 mm at the nozzle exit. The rectangular water nozzle is just at top of the steam nozzle, the height of water nozzle exit is the same size with that of steam nozzle throat, 8 mm, and the width is 10 mm. Besides, there is 10 mm length of straight section at the water nozzle exit, which ensures that the water flow is horizontally injected into the mix chamber. Science there is no gap between the tempered glasses and the steam nozzle, water nozzle as well as the test section, the front and back walls of the rectangular mix chamber are the tempered glasses actually. In addition, altogether 11 groups of measure point are installed on the bottom wall center of the mix chamber for pressure and temperature measurement simultaneously, as shown in Fig. 2(b). In present work, steam and water are injected into the mix chamber though the rectangular steam and water nozzles, respectively. Details of the test conditions are shown in Table 1.

Steam flow rate is measured by a vortex steam flow meter, which is in the range of $(0.75–7.39) \times 10^{-2}$ kg/s with maximum relative deviation of 1.0%. The water flow rate is measured by an electromagnetic flow meter in the range of 0.08–2.78 kg/s with maximum relative deviation of 0.2%. High-temperature pressure transducers used in present work are in the range of 0–1 MPa with maximum relative deviation of 0.1%. Calibrated by a standard thermocouple, the steam and water temperature are measured by the *K*-type thermocouples (diameter 1 mm), which are in the range of 273–473 K with maximum relative deviation of 0.5%. In present work, the steam flow rate, water flow rate, pressure and temperature are in the range of $(1.28–3.84) \times 10^{-2}$ kg/s, 0.47–1.44 kg/s, 0.1–0.5 MPa and 293–423 K respectively, so the